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Evolution of massive stars: main sequence and close to it

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Abstract We discuss the status of current models for the early evolutionary stages of stars in the initial mass range 10–40 $M_{\odot}$. Effects of the pre-main sequence evolution, mass loss, internal mixing, and changes in atomic and nuclear data are outlined and confronted with several basic observational facts, which are unexplained by standard models. We conclude that especially internal mixing processes deserve much more attention in future investigations, and we show why convective mixing may be less efficient than generally assumed, but more mixing should be present in the radiative zones of at least a fraction of all massive stars.

1. Introduction: problems with massive stars

The present paper deals with the early evolution of massive stars. As we shall see, a couple of problems occur when one tries to understand and model those objects. In order to limit the discussion, we restrict ourself to stars with initilal masses less than about 40 $M_{\odot}$, or $L \lesssim 10^{5.5} L_{\odot}$. The evolution of more massive stars, which is largely dominated by mass loss, is discussed elsewhere (cf. Langer 1991, Maeder 1991, Woosley et al. 1992).

Since the developement of 'fast' computers and computer codes for calculation of the internal stellar structure and evolution in the 1950ies, very much progress has been achieved also in the understanding of massive stars. However, when inspecting an observed HR diagram for luminous stars (see e.g. Blaha and Humphreys 1989, Fitzpatrick and Garmany 1990) and comparing it with thoeretical evolutionary tracks or synthetic HR diagrams, a couple of problems are obvious (many of them are discussed also by Fitzpatrick and Garmany; cf. also Leitherer 1991):

i) Too few main sequence (MS) O and early B stars are observed; i.e. the number ratio of MS to supergiant stars is much smaller then typical computed MS to post-MS lifetime ratios.
ii) All evolutionary calculations for massive stars predict a gap between thermaly stable (i.e. quasi-stationary) MS- and post-MS positions in the HR diagram. Observations do not show any indication of a post-MS gap.

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iii) Masses derived from atmosphere models (spectroscopic masses) or radiation driven wind models (wind masses) for O and early B stars are systematically smaller than corresponding masses derived from theoretical evolutionary tracks (cf. Herrero et al. 1990, 1992, Kudritzki and Hummer 1990, Kudritzki et al. 1992).

iv) Current theoretical models leave the question open, whether red supergiants (RSGs) are in general older (i.e. more evolved) or younger than blue supergiants (BSGs). Two kinds of post-MS tracks exist, one leading to He-ignition in the RSG stage and subsequent blue loops (cf. Langer 1991a), the other leading to He-ignition as BSG and subsequent redwards evolution (cf. Maeder 1990 for Z=0.005).

Thus, a survey of the HR diagram in the considered luminosity range (i.e. $10^4\,L_\odot \lesssim L \lesssim 10^{5.5}\,L_\odot$) from left to right does not leave any region without severe problems.

A second basic way of comparison between theory and observations concerns stellar surface abundances. In standard evolutionary calculations, the only way to alter the surface abundances is due to convective dredge up in the RSG stage. Consequently, the surface abundances should be the initial ones before a RSG phase is reached, and afterwards a moderate increase of the N/C ratio and a slight increase in N/O and helium is obtained (Maeder 1987). This picture is in conflict with the observed diversity of N and C line strengths in otherwise similar O and B stars (OBN/OBC-phenomenon; cf. Walborn 1988), which apparently occurs due to CNO-abundance anomalies (Schönberner et al. 1988). Furthermore, a considerable He-enrichment is found in luminous OB stars (Schönberner et al. 1988, Herrero et al. 1992). A further direct evidence for drastic nitrogen enrichment was found in the wind of the progenitor of SN 1987A (Fransson et al. 1989).

In summary, there is a large number of problems which is left by the current standard evolutionary calculations for massive stars. On the other side, the theoretical modeling of massive stars is not straightforward, since a couple of physical processes, which greatly affect the evolution of observable quantities, are quite uncertain. The most relevant of them are probably:

a) the pre-MS evolution
b) mass loss rates
c) internal mixing processes
d) atomic and nuclear data

In the following sections we will discuss the influence of these processes (in the order a-d) on the uncertainties of theoretical evolution sequences and try to single out those effects which could be relevant to the problems mentioned above.

2. Pre-main sequence evolution

We do know only very little about the pre-MS evolution of massive stars. However, what we know seems enough in order to be anxious about the validity of the initial conditions which are generally used in stellar evolution calculations. Those are: chemical homogeneity with cosmic isotope mixture, and hydrostatic

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and thermal equilibrium. Presumably, all these assumptions are wrong in the case of massive stars.

There is no equilibrium structure formed at the onset of nuclear burning, since the contraction time scale of a massive protostar is shorter than its accretion time scale (cf. Yorke 1986). This means that core hydrogen burning starts while the star is still accreting. Therefore no optically visible pre-MS phase of massive stars exists (see also Palla and Pargini 1993). The consequences are unclear, since realistic calculations require at least 2-D hydrodynamic, but Appenzeller (1980) has shown in a 1-D calculation, that hydrogen burning may start with a flash, and subsequently thermal and dynamical oscillations can develope.

One possible consequence of such unstable hydrogen ignition is the development of convection far beyond what will be the convective core during stable hydrogen burning. Since the time scale of conversion of ^{12}C into ^{14}N in the CN-cycle is very short (some $10^3\,yr$, cf. Clayton 1968), ^{12}C may be destroyed in a large fraction of the stellar interior. Depending on the duration of the unstable situation, also ^{16}O and He may be affected. A possible connection to the OBN/OBC-problem (cf. Sect. 1) is obvious. Note, however, that this problem still awaits a serious investigation.

Once accretion onto a massive protostar stops, it may still be situated deep inside a molecular cloud, and consequently be invisible in the optical. This idea is supported by radio observations of so called ultracompact HII regions, which are interpreted as due to luminous O stars moving through a molecular cloud (cf. Churchwell 1990). There number in the Galaxy is comparable to the number of O stars, indicating that those may spend a considerable fraction of their MS lifetime within the molecular cloud wherein they have been formed. This may contribute to the problem of missing MS stars mentioned in Sect. 1.

3. Mass loss

Mass loss rates are a major source of uncertainty in evolutionary computations for massive stars (cf. Chiosi and Maeder 1986). However, due to our restriction on stars with $M_{ZAMS} \lesssim 40\,M_\odot$ we leave out the discussion of stars whose evolution is dominated by mass loss. Especially, we do not discuss the Luminous Blue Variables (cf. Davidson et al. 1989) and the Wolf-Rayet stars (cf. Langer 1989ab) here.

For hot and luminous main sequence and supergiant stars, the radiation driven wind theory (Castor et al. 1975, Abbott 1982, Pauldrach et al. 1986, Blomme et al. 1991) yields mass loss rates as function of stellar parameters, including the metallicity Z. Leitherer and Langer (1991) have estimated the critical ZAMS mass $M_c(Z)$ below which MS mass loss has only negligible effects on the evolution (i.e. $\Delta M/M < 0.05$, ΔM being the total MS mass loss), and found $M_c(Z_\odot) \simeq 32\,M_\odot$ and $M_c(Z_\odot/10) \simeq 80\,M_\odot$. Observationally determined mass loss rates appear to be — on average — somewhat larger than the theoretical ones (cf. discussion in Langer 1989c), possibly due to the instationary character of the wind flow (Owocki et al. 1988, Ribicki et al. 1990). However, mass loss in hot MS and supergiant stages is certainly negligible at low metallicity and at most of moderate importance at solar Z for stars of the considered mass range (cf. also Maeder 1990).

Much more problematic are the mass loss rates of red supergiants, since neither precise observational determinations nor quantitative theories exist (cf. Jura 1991). Jura summarizes evidence for massive stars loosing a significant fraction of their total mass in the RSG stage. This is supported by Stencel et al. 1989, who find expanding massive shells around many supergiants. Spectral features in galactic and Magellanic Cloud supergiants seem to indicate also weaker RSG winds at lower metallicity (Jura 1991), but also this statement can not quantified yet.

Thus, RSG mass loss rates in stellar evolution calculations are more or less arbitrary. We do not know whether the most luminous RSGs do evolve into Wolf-Rayet stars (cf. Schaller et al. 1992, Woolsey et al. 1992). The most firm observational constraint comes from a supernova explosion: light curve and spectral evolution of SN 1987A in the LMC proved the existence of a H-rich envelope of $\sim 10\,M_\odot$ in the progenitor star (Hillebrandt and Höflich 1989), which, for an initial mass of $18-20\,M_\odot$, allows for a total pre-SN mass loss of $\Delta M \lesssim 3\,M_\odot$. Assuming a RSG lifetime of $1.5\,10^5\,yr$ (Langer 1991b) yields $\dot{M}_{RSG} \lesssim 2\,10^{-5}\,M_\odot\,yr^{-1}$ at $20\,M_\odot$ in the LMC.

In summary, the RSG phase is the major problem in following the time evolution of the stellar mass for the stars under consideration. Consequently uncertain are the post-RSG stages (which could be located close to the MS in the HR diagram), especially at high metallicity. Besides direct measurements of RSG mass loss rates and progress in RSG wind theories (cf. Gail 1990), the analysis of Type II supernova light curves may yield important clues for this problem in the near future.

4. Mixing!

Possibly, our ignorance about internal mixing processes are the main source of uncertainty in stellar evolution calculations. This statement is ment in the sense that the physics of the mixing processes itself is uncertain, which affects even standard evolutionary tracks.

4.1 'Convective' processes

First of all, there is the old question about which local criterion should be used to decide whether a layer is convectively stable or unstable. We do not want to repeat lengthy discussions here (cf. Langer 1991a, and references quoted there), but briefly summarize our opinion. According to the linear stability analysis the Ledoux criterion is to be used as convection criterion; layers which are stable according to the Ledoux criterion but unstable according to the Schwarzschild criterion are only vibrationally unstable ('semiconvective'), i.e. such layers are mixed only on time scales much longer than the time scale for convection (Kato 1966, Langer et al. 1983, Spruit 1992). Note that Ledoux- and Schwarzschild criterion are only different in regions of varying mean molecular weight. Furthermore, the validity of the consideration of convection as a local process is questionable, and convective motions may penetrate into layers which are stable according to local criteria ('penetrative convection'; cf. Zahn 1991, 1993).

The efficiency of all three 'convective' processes (note that semiconvection realy is a process quite different from convection), i.e. convection, semiconvection, and penetrative convection, is quite uncertain. Consequently, an efficiency parameter is ascribed to each process, designated as α_{ML}, α_{sc}, and α_{pen} in the following. α_{ML} is the usual mixing lenght parameter, and it is only important in the nonadiabatic (outer) parts of convective envelopes of cool stars, since the temperature stratification is just adiabatic otherwise. The semiconvective efficiency parameter α_{sc} describes the speed of semiconvective mixing, and $\alpha_{sc} \rightarrow 0$ is equivalent to adopting the Ledoux criterion as neutrality condition (cf. Stothers and Chin 1975), while $\alpha_{sc} \rightarrow \infty$ corresponds to the Schwarzschild criterion as neutrality condition (Stothers and Chin 1976). α_{pen} is simply a measure of the distance of penetration beyond the locally determined convective boundary in units of the pressure scale height. Note that only α_{sc} and α_{pen} have a direct effect on mixing of chemical species, while α_{ML} affects mixing only indirectly by changing the envelope structure.

It is beyond the scope of the present work to throughly discuss the possible effects of all three processes on the evolution of massive stars. The mixing lenght parameter is certainly most important for the RSGs. Smaller values of α_{ML} yield a cooler Hayashi line and somewhat deeper convective envelopes. Penetrative convection (often designated as 'overshooting') has been widely used in many evolutionary calculations in the last decade (e.g. Doom 1982ab, Bertelli et al. 1985, Stothers and Chin 1985, Maeder and Meynet 1987, Schaller et al. 1992; cf. Chin and Stothers 1991, for a more complete list), and is thus deeply discussed in the literature. Note, however, that mostly penetrative convection has been considered only for the convective core, but is at the same time ignored for other convective zones in the star. Note further that a couple of theories for penetrative convection ('non-local' convection theories) have been developed in recent years, which compute the penetration distance of convection rather than assuming it by the choice of α_{pen}. The price to be paid is usually that a couple of new parameters appear within those theories. This point, as well as laboratory experiments and 2- and 3-D hydrodynamic simulations for turbulent convection are reviewed by Zahn (1991, 1993).

Semiconvection, on the other side, has been rigorously ignored by most stellar model builders during the past, mainly due to two reasons. First, it was shown that semiconvection is much reduced in the case of mass loss (cf. e.g. Chiosi and Maeder 1986), and, second, is further suppressed by penetrative convection from convective cores (Bressan et al. 1981, Chiosi and Maeder 1986). In our opinion, several fundamental points have been missed in such reasoning. Most important, frequently only the limit of short semiconvective mixing times has been considered, i.e. $\alpha_{sc} \rightarrow \infty$, which leads to the Schwarzschild criterion as neutrality condition (see above). In this way, the effect of molecular weight gradients — which are the basic reason for the occurrence of semiconvection instead of plain convection (Kato, 1966) — are ignored, and the only remaining effect of chemical gradients is the composition dependence of the opacity coefficient and thus of the radiative temperature gradient (cf. Chiosi and Summa 1970). Due to that, the discussion of semiconvection in massive stars was limited to the H/He interface: deep inside massive stars, the opacity is dominated by electron scattering, i.e. there is no opacity effect at the He/C interface. However, semiconvection may be much more important at the He/C interface due to the tendency of growing convective cores during helium burning, in contrast

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to shrinking cores on the main sequence.

Evidence for the importance of semiconvection at the He/C interface in massive stars — and thus for the general tendency of molecular weight gradients to limit convective mixing — comes from the fact that the explosion of SN 1987A as a BSG, which is unexplained in standard computations, can be understood from model sequences which take this effect into account (Woosley et al. 1988, Langer et al. 1989, Langer 1991b). A second independent argument comes from Stothers and Chin (1992), who find — using the recent OPAL opacities (cf. Sect. 5) — that the supergiant distribution of the SMC cluster NGC 330 can only be understood if molecular weight gradients do choke off convection. A third argument comes from the study of Wolf-Rayet stars, which are generally regarded as uncovered He-cores (cf. Langer 1991), and thus provide a direct view 'inside the stars'. The presence of stars of spectral type WN/WC, which probably show simultaneously the products of hydrogen- and helium burning, require a slow mixing process at the He/C interface, which is provided by semiconvection (Langer 1991c). Finally, note that slow mixing in semiconvective zones is also found in laboratory experiments (Spruit 1992).

Consequently, the complete neglecting of molecular weight gradients may be a major shortcoming of most current massive star models. Note that mass loss rates — at least at low metallicity — may be much smaller than widely assumed (cf. Sect. 3), and also the evidence in favour of efficient penetrative convection appears to be largely reduced due to the new generation of opacities (cf. Sect. 5). Consequently, also semiconvection at the H/He interface is of great importance in most massive star models.

A major effect of (slow) semiconvection at the H/He interface is that He-ignition occurs in the RSG phase (cf. Langer 1991a, Stothers and Chin 1992). Consequently, nearly all BSGs should be post-RSGs, i.e. nitrogen enriched. More massive stars develop deeper convective envelopes in the RSG stage, which should lead to stronger nitrogen enhancements for more luminous BSGs (Langer 1991a); this appears to be confirmed in a recent study of galactic B supergiants by Lennon et al. (1992).

4.2 Mixing induced by differential rotation

Several problems listed in Sect. 1 still have no convincing solution due to what is mentioned in the previous sections, e.g. the missing of the post-MS gap in the observed HR diagram, the mass problem (point iii), or considerable nitrogen and helium enrichment of O stars. Rotationally induced mixing may be a way out of many of these problems. Turbulent diffusion due to differential rotation has been proposed to operate in the sun and other low mass stars (cf. e.g. Pinsonneault et al. 1989), but also in more massive stars: Maeder (1982, 1987a) and Langer (1991), using a diffusion formalism proposed by Zahn (1983), found that a considerable nitrogen enhancement in hot and luminous stars may be the result.

In a more recent calculation, also helium is found to be considerably enriched at the surface already on the main sequence, in the case of fast rotation (i.e. efficient turbulent diffusion; also this process is parametrized). Due to the incorporation of semiconvection, it was not found that the star evolved quasi-homogeneous (cf. Fig. 1). The resulting evolutionary track (computed for a $20\,M_{\odot}$ star with $Z = Z_{\odot}/4$) is displayed in Fig. 2, together with a track where

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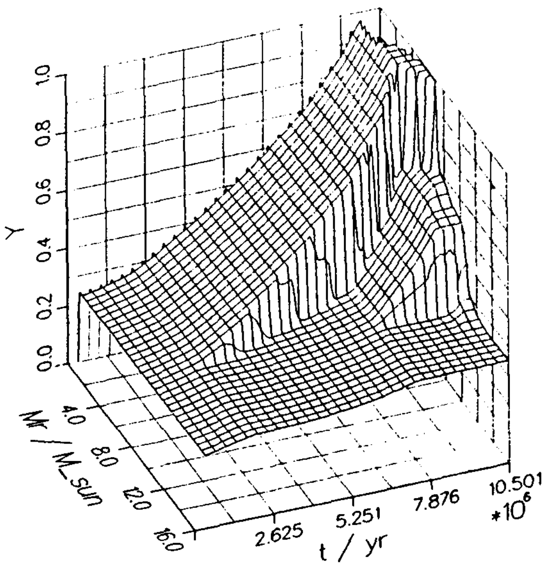

Fig. 1: *Time evolution of the internal helium profile for the 20 $M_\odot$ sequence with efficient turbulent diffusion of Fig. 2 during core hydrogen burning. The concective core region, an intermediate zone, and the envelope can be distinguished. Note the drastic He-enrichment in the intermediate zone and considerable He-enrichment in the envelope ($Y_{surface}$: 0.25 → 0.35).*

turbulent diffusion was switched off. It is obvious from Fig. 2, that the assumption of a variety of rotation rates (and consequently of mixing efficiencies) might contribute significantly to the solution of the problems mentioned above: the post-MS gap is closed half way, the average L/M-ratio is significantly raised, and helium and nitrogen are frequently enhanced at the stellar surface.

The physics of turbulent diffusion is far from being fully understood (despite much progress in recent years; cf. Chaboyer and Zahn 1992, Zahn 1992), and the results mentioned above have to be considered as preliminary. However, turbulent diffusion appears to be a promissing way in order to achieve a closer agreement between theory and observations.

5. Atomic and nuclear data

Clearly, uncertainties in atomic and nuclear data affect the reliablility of stellar models. There is not much room to throughly discuss this item, but as far as early evolution of massive stars is concerned, two basic points should be briefly mentioned here.

First of all, the new radiative opacities of the Livermore group ('OPAL'; Rogers and Iglesias 1992) — which are very successful in removing several long-

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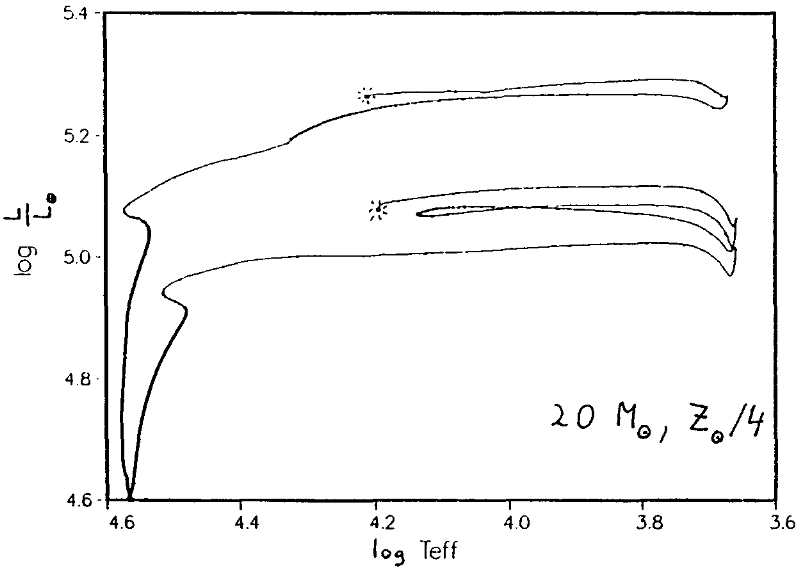

Fig. 2: *Evolutionary tracks for a $20 M_{\odot}$ star computed with efficient turbulent diffusion (upper track) and without turbulent diffusion (lower track) at a metallicity of $Z_{\odot}/4$. Semiconvection is incorporated in both sequences according as in Langer (1991b). Los Alamos opacities are used. The time between two tick marks on the tracks is 10^4 yr. Both sequences spend a considerable fraction of core helium burning as BSG and as RSG. The pre-supernova positions are indicated.*

standing discrepancies between stellar evolution theory and observations (as documented in many papers of this volume) — greatly change all massive star models (cf. Stothers and Chin 1991, Schaller et al. 1992). In particular, they weaken or even remove the requirement of penetrative convection in convective cores of massive main sequence stars (Stothers 1991, Stothers and Chin 1991). Note that consequently semiconvection at the H/He interface becomes more important (cf. Sect. 4.1).

The second item, which is very important to the post-MS evolution, but which is often not discussed at all, is the $^{12}C(\alpha,\gamma)^{16}O$ nuclear reaction rate. It determines how much carbon is transformed into oxygen during core helium burning and thus affects fundamentaly the stellar structure in this phase and beyond. A recent discussion of this point is performed by Weaver and Woosley (1992), who find that massive star nucleosynthesis is only compatible with the solar system abundance pattern for a value of the $^{12}C(\alpha,\gamma)^{16}O$ rate of 1.7 ± 0.5 times that of Caughlan and Fowler (1988). We want to add here, that a simultaneous measurement of the abundances of two of the elements helium, carbon, and oxygen in a WC or WO star could pin down the $^{12}C(\alpha,\gamma)^{16}O$ rate with even higher precision.

The recent progress gives the hope that in the near future atomic and nuclear data will no longer contribute significantly to the uncertainty of massive star models in early evolutionary phases.

6. Summary

Current theoretical models of massive stars — though successful in many respects — still contain considerable uncertainties, and still fail in explaining several fundamental observations (cf. Sect. 1). In the previous sections we have discussed our ignorance concerning the pre-MS evolution, mass loss, internal mixing, and microscopic input in massive star models. The first conclusion which immediately emerges is, that we have an enormous need for further theoretical and observational studies of massive stars; several specific items are mentioned in the text.

For the theoretical models we have shown that internal mixing processes deserve much more attention than they have obtained in the past. We have summarized indications in favour of less mixing in convection zones in the presence of molecular weight gradients (cf. Sect. 4.1) and in favour of more mixing in radiative zones, possibly induced by differential rotation (cf. Fig 2).

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